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Life Prediction Systems for Critical Rotating Components

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INTRODUCTION

With the advent of advanced materials in rotating gas turbine engine components, the methodologies for life prediction of these parts must also increase in sophistication and capability. This talk presents Pratt & Whitney's view of generic requirements for composite component life prediction systems, discusses efforts underway to develop these systems and solicits industry participation in key areas requiring development.

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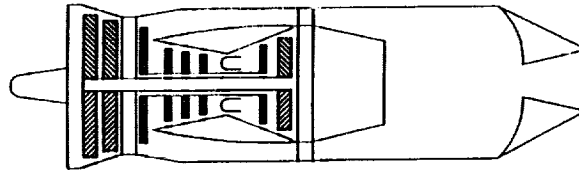
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ADVANCED MATERIAL ROTOR APPLICATIONS

Advanced monolithic materials such as single crystal nickel and composite materials including metal matrix, ceramic matrix and polymer matrix composites are either currently in use or under development and more components are being identified for their potential application in Pratt & Whitney gas turbine engines. Extensive use of composite materials is part of P&W's commitment to producing higher thrust-to-weight engines for military aircraft of the future. Examples of some of the components designated for advanced material technologies are listed here. Because of their low weight and high durability, polymer matrix composites are now being considered for use as fans and fan blades. PMC material technology developments recently have resulted in greater durability and impact absorption and these new forms of PMC's show potential for fan blade applications. In addition to PMC fan components, titanium matrix composite fan blades are being developed and boron aluminum composites have been investigated for use in rotor reinforcement and fan blades. Resistance to impact damage, rather than temperature, is a key driver in fan component development and these metal matrix composites offer benefits in this area. The compressor requires high strength, high temperature, high creep strength and relatively ductile materials. Weight reductions in the compressor can be accomplished by reinforcing the rotor with titanium matrix composite materials, and using metal matrix reinforcements in spacers, coverplates and shafts. Finally, in the turbine, basically, two different advanced material systems will be used. Single crystal nickel blades are currently in use in engines for their extremely high temperature, high strength capability. Single crystal nickel is highly anisotropic and its strength can be directionally controlled, leading to the ability to withstand high axial stresses present in the turbine blades. The second material system is that of ceramic matrix composites which, because of their high temperature and relatively low weight, are ideal for use as heat shields and coverplates. Using them in conjunction with monolithic materials makes them viable as reinforcements in the turbine rotor.

Fan
Lightweight MMC Rotor
PMC Blades

Compressor
Ti MMC Rotors and Spacers
MMC Coverplates and Shafts



Turbine
S/C Nickel Blades
CMC Reinforced Rotor
CMC Heat Shields and Coverplates

LIFE SYSTEM REQUIREMENTS

The goal of a life prediction system is to accurately evaluate the remaining life of a component given its stress state, geometry, environment, existing damage and any other factor which might contribute to the part's demise. The cost to develop such a system for conventional materials is significant. Gas turbine engine environments operate at high temperatures for extended periods of time under high inertial loads and vibratory stresses. These loadings may also interact in a nonlinear manner. In laboratory testing, the complex in-service conditions are seldom reproduced to give accurate assessment of a component's damage tolerance. We rely on tests which intentionally isolate damage and damage progression modes in order to develop simple mechanistic models for assessing the life of a part. It is important that these modes be mechanistic, or physically-based, since their use is required over a wide range of conditions and it is impossible to reproduce all conditions in the laboratory. We therefore need models which can be interpolated and linearly combined to yield predictions of behavior at any service condition. Further, the Engine Structural Integrity Program (ENSIP) requires that all components classified as safety critical and made from composite materials must be capable of sustaining specified damage and continue to function without requiring repair for their design service lives. This means that we must be able to show that when a part is damaged, it will be able to continue operating with that damage until the design service life is reached. In conventional materials we take a fracture mechanics approach to determine if the stresses are below a threshold value or, if higher than this, if the stresses are within the range that a flaw will grow at a controlled rate. For advanced materials to satisfy ENSIP, we need to show that either the materials will contain no defects, or if they do, that the predicted behavior of the material will not lead to damage propagation such that part rupture will occur during a specified maintenance-free operational period.

- Mechanistic
- Satisfy ENSIP Requirements

LIFE SYSTEM ADVANCEMENTS NEEDED

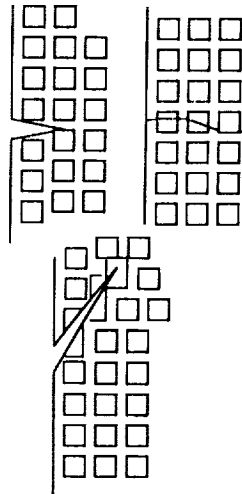
Damage propagation predictions in conventional monolithic materials are accomplished through classical fracture mechanics approaches where a single crack dominates, controls the component's capability to withstand load and propagates according to a growth rate law which is a function of the crack tip stress intensity. The approach is primarily dependent on the geometry of a crack and has been shown to yield good predictive capability when used for component life from a specimen database. Damage in advanced materials, however, is not limited to self-similar or even mixed-mode single cracks and fracture mechanics approaches may not lend themselves to an advanced material life system. Take, for example, the case of cracking in single crystal nickel alloys. The microstructure of these alloys contains cuboidal, ordered precipitates which exhibit different properties than the matrix material. In a way these alloys are two-phase composites and to predict their fracture behavior we must transcend conventional fracture mechanics wisdom and instead relate the fracture mode, not just to geometry, but to the energy state required to move dislocations across precipitate boundaries and along active slip planes. Metal matrix composites also show different fracture behavior depending on temperature, material, ply layup and stress level. Take, for example, three crack geometries which have been observed in titanium matrix composites. In each case, fiber bridging has been observed to some extent. If we are to predict lives of components with this kind of fracture behavior, we must not only consider the effects of crack tip stress reduction due to shear lag but we also need to be able to predict crack geometry based on constituents and conditions. All these are advancements which need to be made if these materials are to be used in fracture-critical parts.

Multiple Discrete Damage Modes

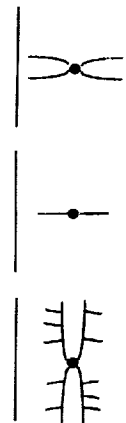
Monolithic



Single Crystal Nickel



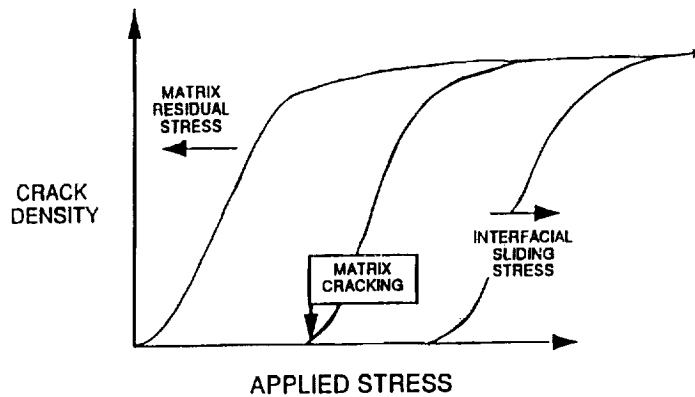
MMC



LIFE SYSTEM ADVANCEMENTS NEEDED

Ceramic and polymer matrix composites exhibit even different damage behavior. The damage associated with these materials no longer can be simply associated with a single dominant or pair of discrete cracks. We must now consider damage that is not always distributed uniformly or periodically within a damage zone. As an example, we can consider crack density, rather than crack length, as a damage parameter and address the probability of fiber failure. The variation of these parameters and the influence drivers such as stress state, temperature, and environment have on the parameters will have to be characterized. In addition, CMC and PMC engine components will require more sophisticated architectures than unidirectional plies so models describing damage in these complex systems will be required.

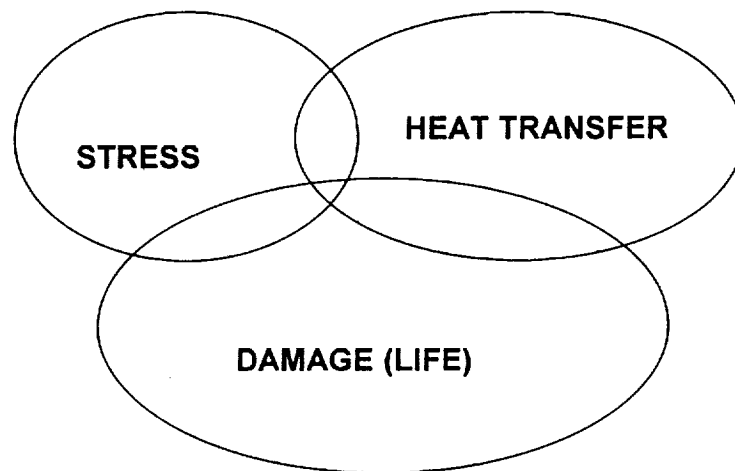
Distributed Damage Modes Require Methods which Combine Mechanics and Stochastics



LIFE SYSTEM ADVANCEMENTS NEEDED

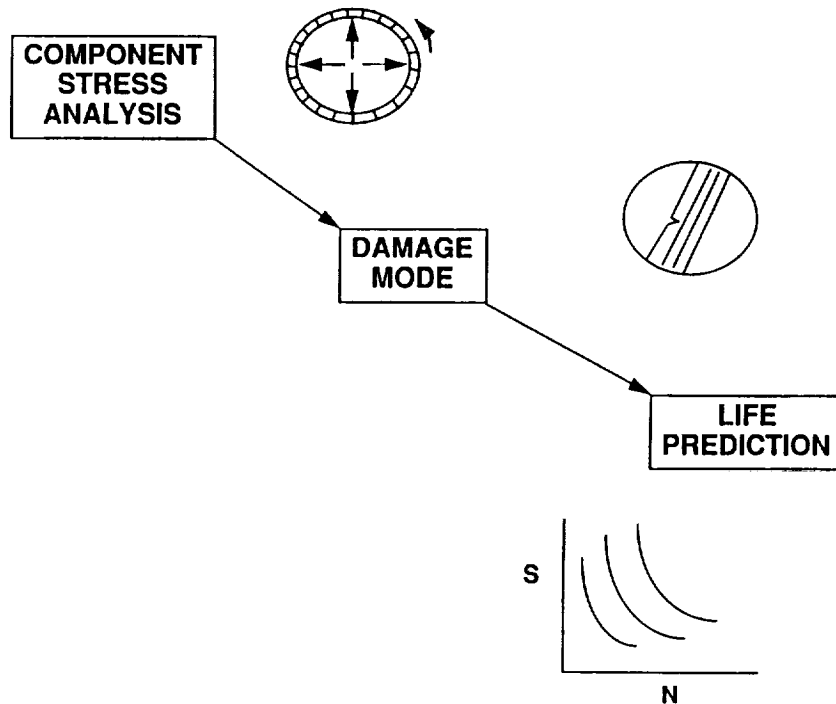
A further complication in the life prediction of ceramic matrix composites for high temperature applications is related to the heat conduction properties of the components. Heat transfer is especially important in the structural analysis of these components. When damage occurs in a CMC structure under high thermal loading, aberrations in the local heat transfer characteristics occur and cause severe local temperature gradients and high thermal stress states. These high stresses lead to greater damage and the cycle continues in a highly coupled manner. This interaction must be accounted for in a CMC life system.

CMC Behavior Highly Coupled System



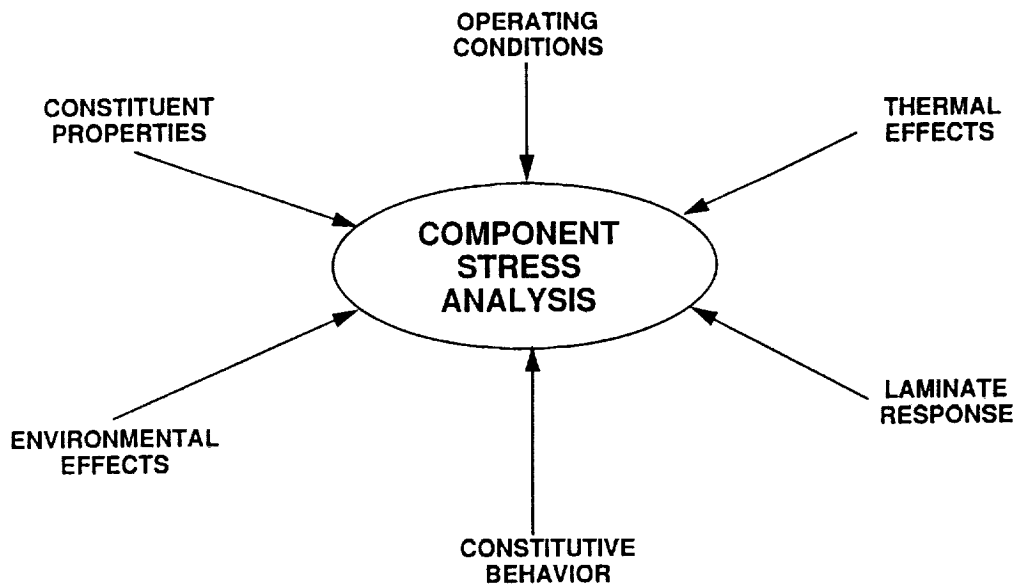
ELEMENTS OF A LIFE SYSTEM

Basically, we can identify three elements which contribute to a life prediction system. First we need to determine the stress state of the component by way of a numerical stress analysis. Once this state is known we can identify the mode of damage most likely to occur based on the constituents of the material, the loading configuration and the material properties. The damage mode will determine which analytical models for damage propagation are relevant for use in determining life and this decision point is the most distinct difference between a conventional life system and a system for advanced materials. Finally, the life calculations are performed using analytical models which predict damage initiation, propagation and failure. Each of these three elements will be described in more detail in the next three slides.



ELEMENTS OF A LIFE SYSTEM

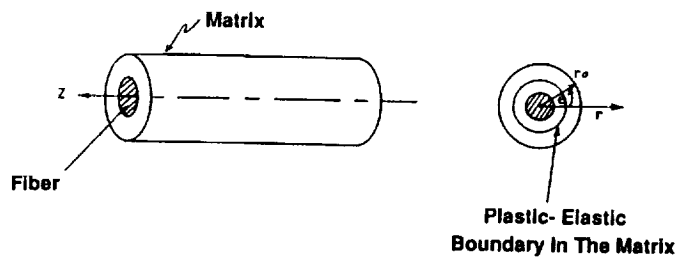
The component stress analysis is a global analysis that incorporates composite behavior through constitutive modeling at a local level. This means that a good description of stress-strain behavior at the microlevel is required to give a good description of what happens at the laminate level. Several factors play important roles in the micro and macro level mechanics. These include thermal effects (since properties change as functions of the temperature), operating conditions, laminate response, constituent properties and the constitutive behavior, and environmental effects. This last factor is especially important in CMC high temperature applications since oxidizing atmospheres can lead to fiber degradation if exposure by matrix cracking occurs. It is important to understand how each of these factors interact if accurate stress analysis is to be performed.



STRESS ANALYSIS REQUIREMENTS

The stress analysis requires micromechanical stress/strain behavior models in order to incorporate the behavior at the local level into the global behavior predictions. Current available models rely on concentric cylinder approaches. Often these approaches inaccurately model the interface conditions or the matrix outer radius boundary condition. Models are being developed, for example, that of Naik and Crews, which better approximate the tractions on the matrix outer edge boundary and these can be readily implemented in existing component stress analysis codes. Requirements for such models include the ability to model imperfectly bonded interfaces to account for friction and wear at the fiber/matrix interface, multiaxial loading to account for transverse, shear, tension and compression conditions, temperature dependent materials properties which are important in TMF and thermal residual stress calculations, and yielding in the matrix.

Need Good Micromechanical Stress/Strain Behavior Models

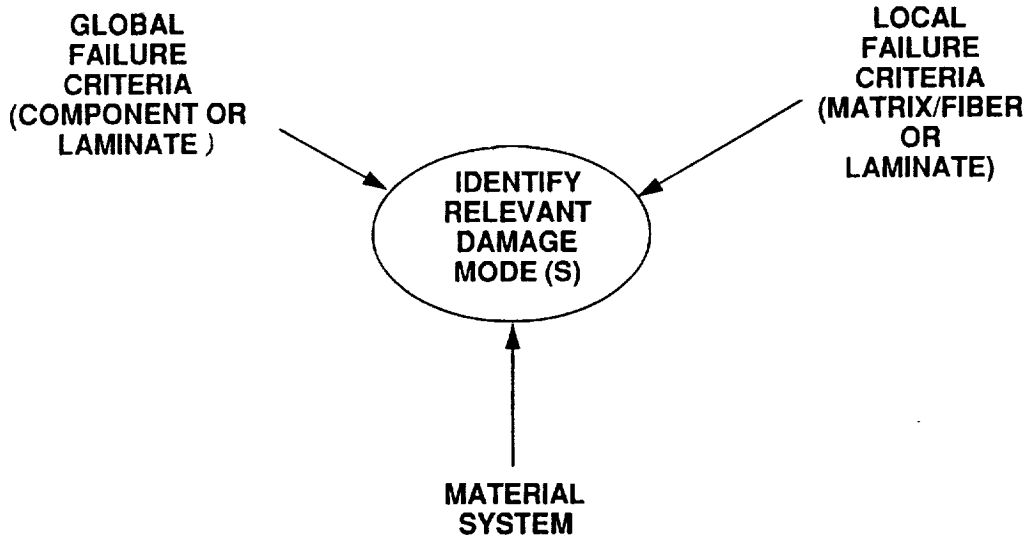


Assumptions:

- Imperfectly bonded interfaces
- Elastic transversely isotropic fiber
- Multiaxial loading
- Temperature dependent materials properties
- Elastic-plastic isotropic matrix

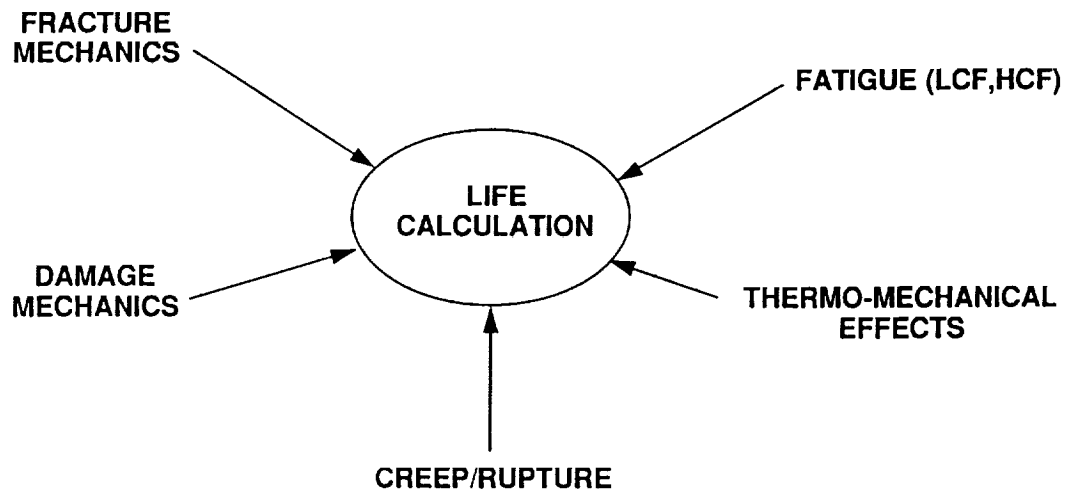
ELEMENTS OF A LIFE SYSTEM

Before a life system can be established, failure criteria are needed. Depending on the needs of the component, these could be on a global scale (for example, through-thickness cracking of a component or laminate), or on a local level (for example, multiple fiber fracture, matrix cracking or small-scale laminate failure). In addition, because different material systems yield different types of damage, the material system and the failure criteria are the inputs to a map which enables identifying the relevant damage mode or modes which may lead to failure. This failure mode map is a key part of a composite life prediction system and the development of it will rely heavily on parametric experimentation.



ELEMENTS OF A LIFE SYSTEM

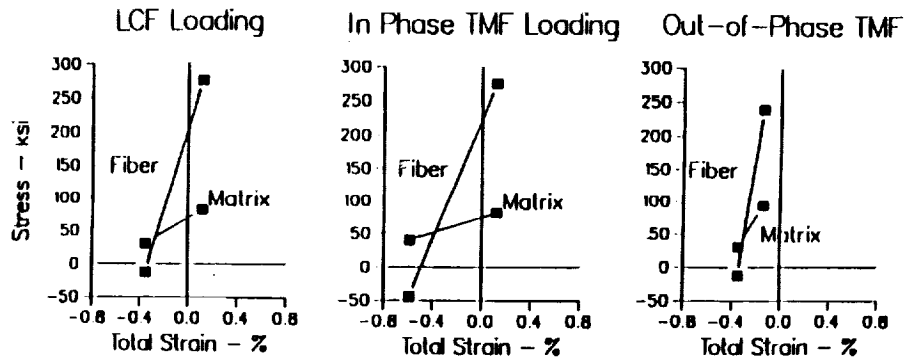
The final elements of a composite life system are the individual models which estimate the rate of damage progression. These elements can be treated as individual modules addressing several different modes of damage. Fracture mechanics based models will be used for cases where discrete damage leads to failure. These are appropriate for MMC materials that fail by a limited number of dominant matrix cracks, for fiber matrix separation due to shear loading, or for delamination caused by interlaminar shear. Fracture mechanics based models have advantages over other model types since they have a large experience base, are easily incorporated in existing life systems for conventional materials and they, to a great extent, rely on material properties of the matrix alone, reducing the number of tests required on the composite materials. Damage mechanics approaches are being considered for cases where distributed damage controls fail. CMC and PMC materials are candidates for this type of model. It is noted that incorporating damage mechanics into life systems will require a change in philosophy from current life analysis methods. Initiation lives are important to predict and so high and low cycle fatigue models will be incorporated as will TMF and creep models. This latter damage mode is especially important in some composite materials applications, for example, the High Speed Civil Transport, where the design service life is 18,000 hours. It is noted that characterizing material behavior for these long exposures will require accelerated test techniques and better extrapolation modeling.



TMF AND DAMAGE INITIATION MODELING

Several damage models have already been investigated at P&W. The Smith-Watson-Topper model for predicting stress-strain response has been used to evaluate LCF and TMF data obtained in tests of Ti-15-3/SCS-6. LCF isothermal loading and TMF in-phase and out-of-phase loading were analyzed. Stress-strain states in the fiber matrix for each of these loading modes were calculated from a concentric cylinder constitutive model. The resultant stress-strain data were reduced to a single parameter, effective stress as shown here. It is noted that an additional parameter which accounts for thermal residual stresses induced by cooling from composite consolidation has recently been developed and is being studied.

Stress-Strain Response from Fatigue Data



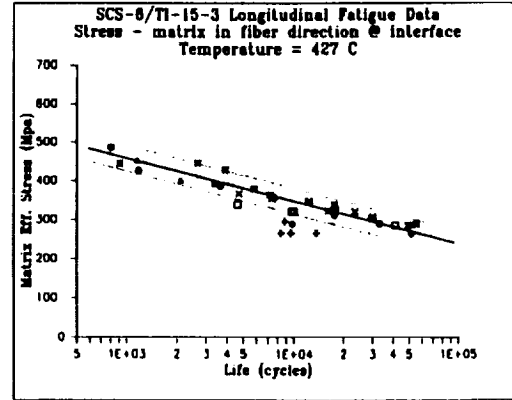
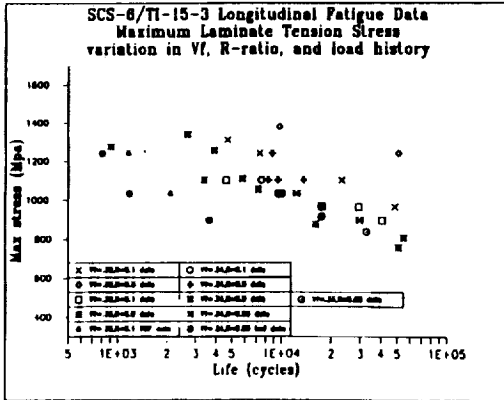
Smith-Watson-Topper Parameter
Effective Matrix Stress

$$\sigma_{eH} = \sqrt{\sigma_{max} \frac{\Delta \epsilon}{2} E}$$

TMF AND DAMAGE INITIATION MODELING

The results of the SWT analysis are shown here. The parameter effectively collapsed the longitudinal fatigue data to a single line relating life to effective stress. More work will be performed to assess this model's ability to accurately predict fatigue lives of different materials under different loading conditions.

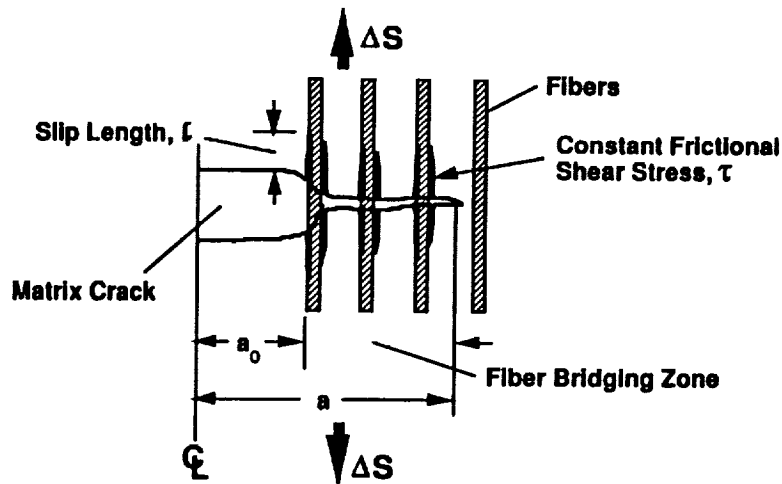
Longitudinal Fatigue Life



CRACK GROWTH MODELING

Fracture mechanics modeling for predicting the crack growth rates when dominant cracks exist has included the evaluation of large-scale bridging models first presented by Marshall, Cox and Evans and by Budiansky, Hutchinson and Evans for monotonic loading and later developed for cyclic loading by McMeeking and Bao. Our evaluation has included the use of TiMC crack growth data from outside sources. It appears that the fiber bridging models, which depend to a large extent on the frictional shear stress (τ) at the fiber - matrix interface, have a useful place in the analysis of crack propagation in composites that fail by fiber-bridged cracks. The use of the figure, developed by W. S. Johnson and associates, is gratefully acknowledged.

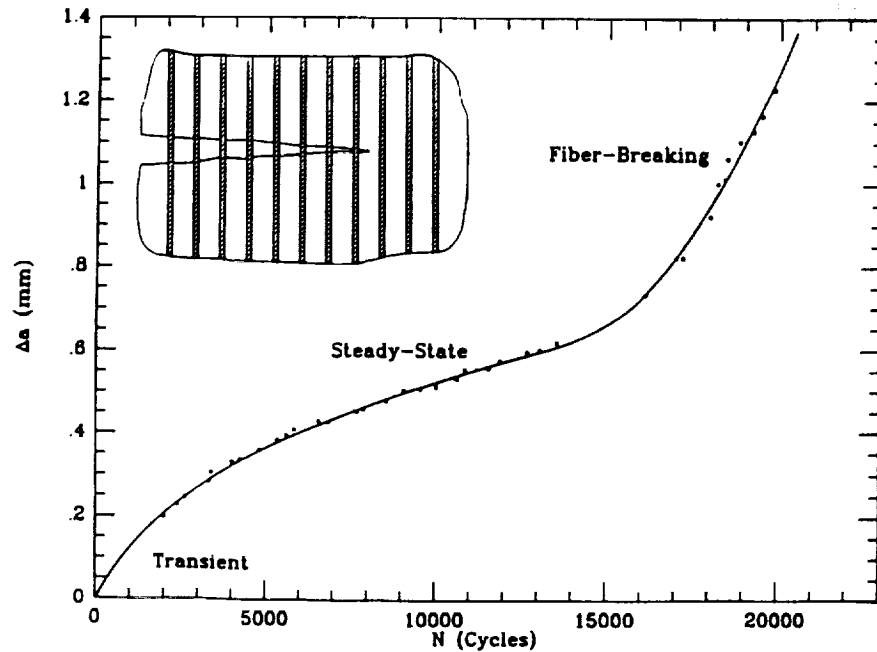
Mode I Fatigue Loading with Fiber Bridging (McMeeking, Evans, Bao)



CRACK GROWTH MODELING

An advantage of the McMeeking and Bao work is that it uses τ to predict fiber failure caused by fiber overstress. Onset of fiber breaking leads to rapid crack propagation, shown here by the data of Walls and Zok, and could be used as a failure criterion. Disadvantages of this approach relate to the difficulty in characterizing τ and the observations which suggest that τ is not a constant. Rather, τ changes with number of fatigue cycles and varies as a function of position along the fiber. It is expected that the shear lag models which use τ to predict crack propagation will incorporate it as an empirical fitting parameter rather than a material property.

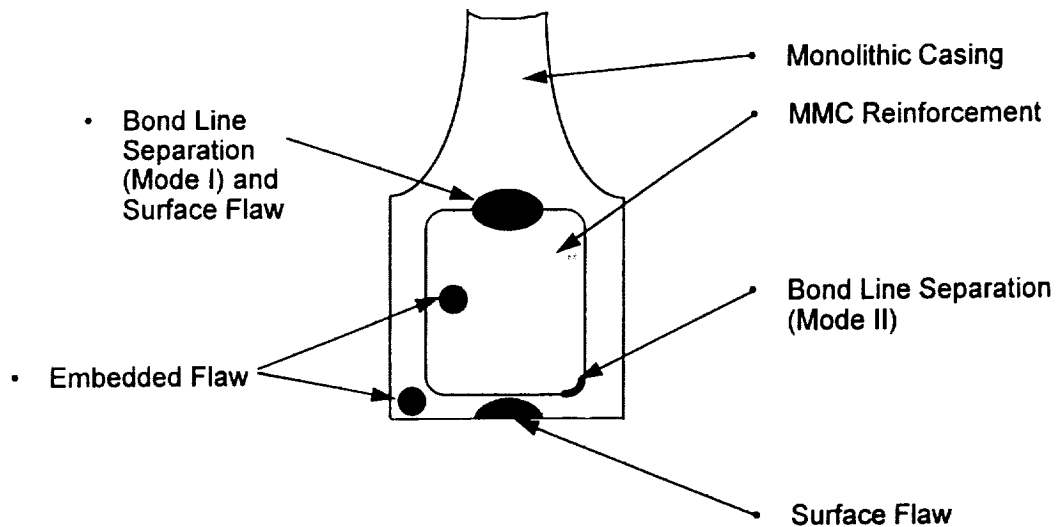
Mode I with Fiber Bridging (Walls and Zok, UCSB)



CRACK GROWTH MODELING

Fracture mechanics approaches depend to a great extent on the geometry of the crack. In order for these models to be viable for component durability assessment, solutions for appropriate flaw geometries must be established. For the case of a ring reinforced with a metal matrix composite, several flaw geometries are anticipated. These include penny-shaped cracks embedded in the composite reinforcement, surface flaws starting in the monolithic casing and propagating into the MMC core, and case-core bond line separation in both Mode I and Mode II. These are not simple problems. Current crack bridging models have not transcended the two-dimensional edge- and center-crack geometries and techniques for either extending current solutions to three-dimensional approximations or using numerical schemes for three-dimensional modeling will have to be developed.

Specific Geometry Requirements

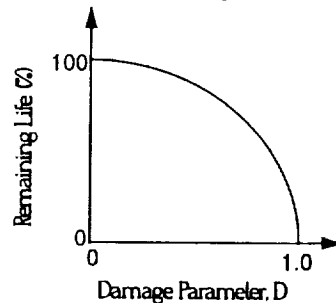


DAMAGE MECHANICS MODELING

Damage mechanics modeling is a new concept in component life analysis but may be required for predicting life of new materials that exhibit distributed damage. Instead of characterizing damage by a crack length, damage mechanics models use parameters that are degraded by accumulation of damage, such as stiffness, strength, or coefficient of thermal expansion. These models are appropriate for CMC's, PMC's and IMC's. An issue to be addressed before this approach can be successful is the question of the rank of tensor that is appropriate for these materials. In other words, how directionally dependent are the parameters on the damage, or, how directionally dependent is the damage progression on material anisotropy and loading configuration? In addition, the damage parameter itself will have to be established, bearing in mind that inspection requirements and parameter measurement will be important in the life analysis development and calculation. For example, if composite strength is the damage parameter, the number of specimens required to characterize the model will be significant compared to a parameter which can be characterized nondestructively.

Accumulation and Evolution of Distributed Thermomechanically Induced Microstructural Defects

- Continuum Damage Mechanics (CDM) - Macro representation of micro damage
- Appropriate for CMC's , IMC's, PMC's through tensorial CDM
- Model Form : $D = f \left(1 - \frac{\dot{A}}{A} \right)$ for \dot{A} ...measured property
A...property of undamaged state
- Damage parameters: stiffness, strength, CTE, etc.



PRIMARY DEVELOPMENT NEEDS

In conclusion, P&W is committed to the development of a life prediction system for advanced composites. However, there are several key areas requiring substantial development and industry cooperation for their solution. P&W has been successful with other cooperative efforts such as the one recently with NASA Lewis Research Center in which three composite rings were fabricated and tested and we look forward to future efforts in our quest for a state-of-the-art life prediction system. Specifically, I leave the following list of some critical areas requiring development. Of high priority is the incorporation of interface element layers and matrix plasticity in micromechanical models for stress-strain behavior. Also important for the near-term is the ability to track and predict damage progression in the complex fiber architectures anticipated for CMC and PMC components. Experimental characterization and related computational efforts are needed to develop failure mode maps for all composite materials under investigation. Accelerated test and analytical techniques are required to relate long-term behavior in service environments to shorter-term behavior in the laboratory. Finally, before PMC components can be used in engine applications, significant effort must be expended to understand damage progression and material behavior in these materials.

- Stress-Strain Micromechanical Behavior
 - Interface element layer to simulate imperfect fiber/matrix bond
 - Capability for modeling Elastic-Plastic matrix
- PMC Materials Behavior and Modeling
- Ability to Track Distributed Damage/Different Fiber Architectures
- Experimental/Computational Damage Mode Mapping
- Accelerated Test and Analysis Techniques